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Original communication

The effect of the prone maximal restraint position with and without weight force on cardiac output and other hemodynamic measures

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ABSTRACT

Background: The prone maximal restraint (PMR) position has been used by law enforcement and emergency care personnel to restrain acutely combative or agitated individual. The position places the subject prone with wrists handcuffed behind the back and secured to the ankles. Prior work has indicated a reduction in inferior vena cava (IVC) diameter associated with this position when weight force is applied to the back. It is therefore possible that this position can negatively impact hemodynamic stability.

Objectives: We sought to measure the impact of PMR with and without weight force on measures of cardiac function including vital signs, oxygenation, stroke volume (SV), IVC diameter, cardiac output (CO) and cardiac index (CI).

Methods: We conducted a randomized prospective cross-over experimental study of 25 healthy male volunteers (22–43 years of age) placed in 5 different body positions: supine (SU), prone (PR), prone maximal restraint with no weight force (PMR-0), prone maximal restraint with 50 lbs added to the subject's back (PMR-50), and prone maximal restraint with 100 lbs added to the subject's back (PMR-100) for 3 min. Heart rate (HR), blood pressure (BP), and oxygenation saturation (O_2 sat) were monitored. In addition, echocardiography was performed to measure left ventricular outflow tract diameter (LVOTD), and SV, CO, and CI were then calculated. Data were analyzed using repeated measures ANOVA with pair-wise comparisons when appropriate to evaluate changes with each variable with respective positioning.

Results: Despite a small decrease in SV between SU and PMR positions, there were no statistically significant differences in CO between the 5 different positions. There were also no differences in CI between positions other than a small decrease when comparing SU and PMR-50 only (mean difference −0.39 L/stroke, $p = 0.005$). There was no evidence of hemodynamic compromise in any of the PMR positions when evaluating HR, MAP or O_2 sat.

Conclusions: PMR with and without weight force did not result in any changes in CO or other evidence of cardiovascular or hemodynamic compromise.

1. Introduction

Prehospital and law enforcement personnel often confront violent and sometimes dangerous individuals who require physical restraint in order to ensure the safety of the restrained individual, on-lookers, and the officers themselves. Numerous physical restraint techniques have been developed and established to subdue and control such individuals in the field. The prone maximal restraint position (PMR), often referred to as the hobble or hogtie position has been used extensively by first responder personnel. This position places a subject prone with their wrists handcuffed behind the back and secured to the ankles with varying degrees of freedom allowed for the movement of the legs.[1,2]

Because of reports of sudden deaths of individuals placed in this restraint position, interest has arisen regarding the physiologic effects of the PMR position, as the exact cause of death in many of these cases remains unclear.[3–6] It has been suggested that PMR, as well as

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the force required to place combative individuals in that position, can adversely impact cardiovascular function and hemodynamic parameters, such that restrained individuals may be at risk for significant morbidity and mortality.[7–9] However no previous study has directly addressed whether weight force applied to the back while in the PMR position adversely affects cardiac output (CO).

In this study, we assessed sonographically-measured left ventricular outflow tract diameter (LVOTD) and other vital signs to determine whether body position or restraint technique with or without weight force can cause changes in CO or hemodynamic status that could produce a significant clinical effect.

2. Methods

2.1. Study design

We performed a randomized, cross-over comparison controlled trial in 25 male volunteer subjects. The study protocol was approved by our institutional human subjects research review committee.

2.2. Study setting and population

Volunteer subjects were recruited from the university campus by study investigators. No subjects were excluded based on age, ethnicity or health history. The study was conducted in a university hospital patient care room. All subjects received a small monetary gift card of their choosing for participation in this study.

2.3. Study protocol and measurements

Baseline data from each subject were collected including age, weight, height, and body mass index (BMI). Each subject then underwent 5 separate trials in different body positions in random order: supine (SU), prone (PR), prone maximal restraint without weight force (PMR-0), prone maximal restraint with 50 pounds of weight on the center of the back (PMR-50), and prone maximal restraint with 100 pounds of weight on the center of the back (PMR-100).

In the SU group, subjects were positioned in a supine fashion with arms at their sides on a standard hospital patient examination gurney. For PR and PMR positions, the subject lay prone on a special wooden board constructed with a 20 × 20 cm cutout around the chest area to allow for a sonographic probe during echocardiographic evaluation. For PMR positions, the subject lay prone with wrists secured behind the back and ankles secured together within 1–2 feet of the wrists via restraint straps. In order to simulate the force often required to place individuals in the PMR position, standardized plate weights were placed on the back of subjects for PMR-50 and PMR-100 (Fig. 1).

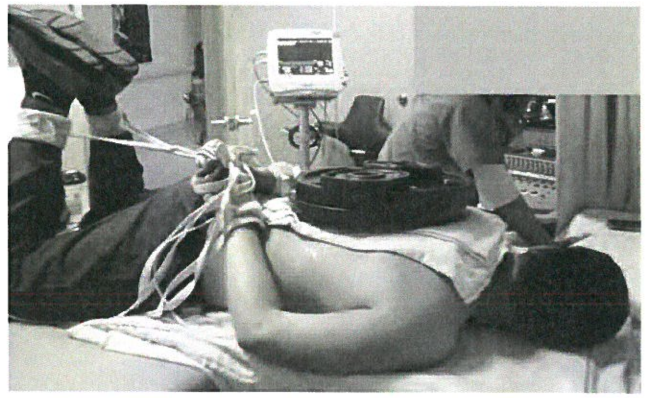

Fig. 1. Photograph of study subject placed in PR-100 position with wrists secured behind the back and ankles secured together within 1–2 feet of the wrists via restraint straps.

The order of each position trial was randomized and each subject served as their own control as a cross-over comparison investigation. The subject remained in each position 3 min before any measurements were collected to allow for physiological adjustment to the new position. Between each trial, subjects rested at least 5 min before being placed in a new position for repeated study measurements.

Measurements obtained from each subject included heart rate (HR), oxygen saturation (O_2 sat), and systolic and diastolic blood pressure; (SBP, DBP), Mean arterial blood pressure (MAP) was then calculated from the SBP and DBP.

While in each position, an RDMS-certified, Emergency Medicine board-certified physician conducted an echocardiographic evaluation on the subject, obtaining sonographic images of the heart as well as abdominal sonographic images of the inferior vena cava (IVC). A Zonare ultrasound machine with a phased-array probe (P4-1C) was used to these obtain images. In each position, a parasternal long axis (PLAX) view was obtained to measure the left ventricular outflow tract at its maximal diameter (LVOTD) (Fig. 2). Additionally, in the same PLAX view, the LVOT velocity time integral (LVOT VTI) was obtained utilizing cardiac ultrasound software designed to measure this variable as a reflection of the velocity of blood traveling during systole. Cardiac output (CO) was then determined by the equation,

$$HR \times SV = CO$$

and SV was calculated based upon the following equation,

$$SV = \pi(LVOTD/2)^2 \cdot LVOT\ VTI.$$

Cardiac Index (CI) was then calculated by the following,

$$CI = CO/BSA$$

Where BSA was calculated body surface area according to the Mosteller formula[10] of,

$$BSA = \sqrt{(\text{Weight (kg)} \cdot \text{Height (cm)}/3600)}$$

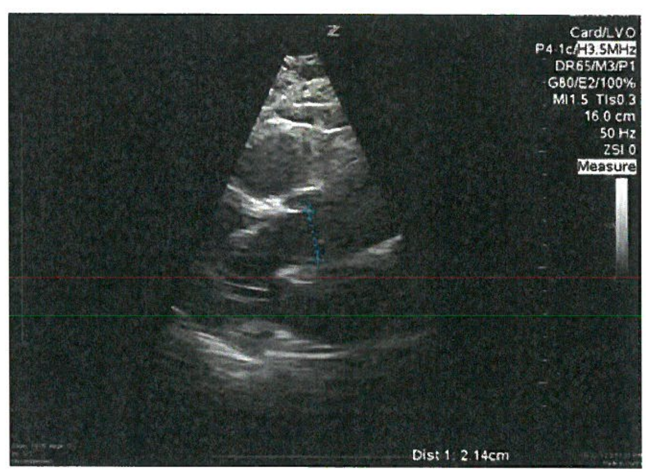

Fig. 2. Ultrasonographic image of heart measuring left ventricular outflow tract diameter (LVOTD).

2.4. Data analysis

Our primary outcome measures were CO and CI. Secondary measures included SV, HR, MAP, and IVC diameter. For data analysis, SAS software was utilized to perform a repeated measures mean comparative analysis of variance (ANOVA) as well as pair-wise comparisons when indicated. p-Value was set at 0.05 with Buonferroni correction for multiple comparisons when appropriate.

3. Results

All 25 subjects completed the study in each of the 5 positions, resulting in 125 experimental observations for comparison. Subjects had an average age of 31.08 years (range 22–42 years) and average BMI was 26.6 kg/m^2 (range 23.6–35.3 kg/m^2).

The results of the study are as shown in Table 1. For CO, there were no significant changes between any of the positions. Mean CO in the SU position was higher than PR position (+0.61 L/min), but this difference was not statistically significant on pair-wise comparison. CO differences between PR and the PMR positions were variable with no progressive changes or statistically significant differences between positions on pair-wise comparisons. A similar variable pattern was seen with CI with no statistically significant differences other than a decrease in the PMR-50 position compared to SU (−0.39 L/min/m^2; $p = 0.005$), but no difference seen with the PMR-100 position compared to SU (Fig. 3).

The minimal changes in CO and CI were reflective of similar changes seen in HR and SV. PMR-100 had a statistically significant increase in HR compared to other positions but all HRs remained within the normal range in all positions. In the PMR-50 and PMR-100 positions there was a small, but statistically significant decrease in SV compared to SU, but no differences compared to PR or PMR positions (Fig. 4).

There were no significant differences in IVC diameter other than PMR-100 where IVC was smaller compared to SU and PR positions (−0.25 cm, $p = 0.001$; −0.44 cm, $p = 0.004$, respectively). At no point was IVC collapse noted on ultrasonography.

These minimal changes in IVC and SV had no impact on hemodynamic parameters. In fact, in the PMR-100 position there was a significant increase in MAP compared to all other positions including SU. Additionally, MAP in the PMR-50 position was significantly higher compared to the PR position (+3.68 mmHg, $p = 0.004$). O_2 sat remained normal throughout the experiment with no differences between positions (Fig. 5).

4. Discussion

The unexpected, sudden death of an individual under arrest or in physical restraint is a rare, but well-known phenomenon in law

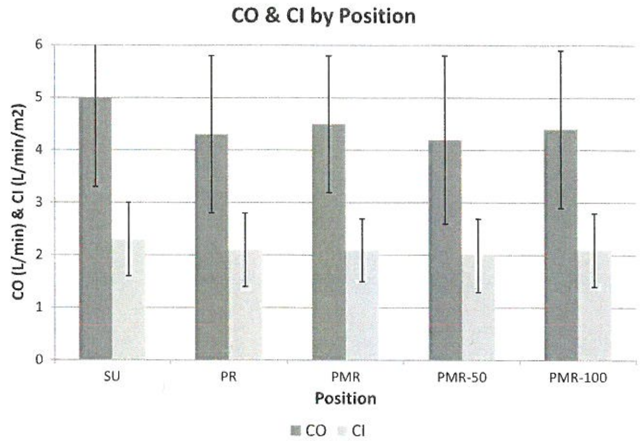

Fig. 3. Mean CO & CI by position with standard deviation bars.

enforcement and emergency pre-hospital care settings.[11,12] As the actual cause of death in many of these cases is unclear, they have been attributed to any number of etiologies including illicit drug use, hypercatecholaminergic syndrome, stress cardiomyopathy, underlying cardiac disease, excited delirium, and trauma.[13] Because the circumstances of these deaths often occur in temporal proximity to responding law enforcement and prehospital personnel, it has been suggested that the actions of first responders utilizing physical restraint and other techniques (including pepper spray and conducted energy devices such as Tasers®), may play a causal role in these deaths.[14–16]

Previously, it had been postulated that the hogtie, hobble, or the PMR-0 position placed individuals at risk for asphyxiation from ventilatory compromise from so-called "positional asphyxia".[7,17,18] However, studies investigating the position have found that while PMR, and even just the prone position itself, results in a small restrictive pattern on pulmonary function testing, there are no studies indicating that the position leads to hypoventilation or hypoxia, and multiple studies indicating there is no effect upon oxygenation.[19–21] Subsequently, it was then hypothesized that the additional force applied to a subject's back while being placed or held in PMR (such as when law enforcement personnel place pressure on an individual while restraining them) could lead to a greater decrement in respiratory function because this weight might constrict the chest and abdomen and result in so-called "restraint asphyxia".[2,6] However, all studies examining respiratory and ventilatory function in the prone restraint position with simulated weight force of up to 225 lbs did not find evidence of respiratory impairment, hypoxia or hypoventilation to indicate a significant risk for asphyxiation.[22–24]

Table 1
Cardiovascular parameters (mean, SD) by position.

	SU		PR		PMR-0		PMR-50		PMR-100	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CO (l/min)	5.0	1.7	4.3	1.5	4.5	1.3	4.2	1.6	4.4	1.5
CI (L/min/m^2)*	2.3	0.7	2.1	0.7	2.1	0.6	2.0	0.7	2.1	0.7
IVC (cm)*	2.6	0.6	2.5	0.4	2.4	0.5	2.3	0.4	2.1	0.5
HR (bpm)*	70.7	12.6	68.5	10.5	72.1	13.0	71.8	12.8	75.8	13.8
SV (mL)*	69.9	19.4	63.3	18.3	62.3	16.8	58.0	19.4	57.9	18.1
MAP (mmHg)*	88.1	6.5	86.0	7.2	88.8	8.2	89.7	8.1	95.2	10.4
O_2 sat (%)	98.7	1.1	98.4	1.9	98.3	1.9	98.0	1.7	98.4	2.0

*Statistically significant differences.
CI: SU vs PMR-50.
IVC: PMR-100 vs SU, PR.
HR: PR vs PMR-100.
SV: SU vs PMR-50, PMR-100.
MAP: PMR-100 vs all other positions.

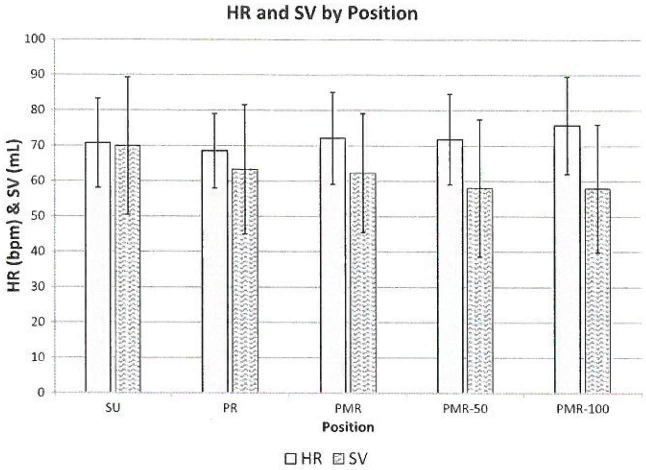

Fig. 4. Mean HR and SV by position with standard deviation bars.

Other work has focused on the potential impact of PMR and weight force on cardiovascular function and hemodynamic status. In a small study, Roeggla et al. reported a significant drop in CO in 6 subjects placed in the prone hobble restraint for 5 min.[7] However, the cardiovascular parameters in this study were measured by a non-invasive finger probe, which measurements have been shown to vary simply by finger and body position.[25,26]

In another small study, Krauskopf et al. placed 6 healthy volunteers in the prone position with varying weight force on the back from 0 to 25 kg, measuring inferior vena cava (IVC) size and flow, SV, CO, CI, HR and MAP by sonography and impedance cardiography. The investigators found significant decreases in IVC size, but no significant difference in cardiovascular parameters including CO and CI comparing no weight force with weight force.[9] Moreover, impedance cardiography has shown significant variability in measurement just by body position alone.[27]

In a more recent study, Ho et al. reported on IVC size, HR, and BP measurements in 25 subjects in the standing, prone, and prone with 45 and 67 kg weight force on the thorax.[8] Similar to Krauskopf, the investigators found significant, progressive decreases in IVC size, but no changes in HR or BP measures. However, there was no comparison with the supine position and the order of positions does not appear to have been randomized, raising the possibility of a confounding temporal bias. The authors postulated that the decrease in IVC might be indicative of a drop in central venous return and cardiac output that could lead to cardiovascular collapse. However, no determination of CO was made and their hypothesis was based only upon the use of IVC size as "a marker of cardiac filling and, by inference, cardiac output".[8] Further negating their hypothesis was the normal maintenance of HR and BP.

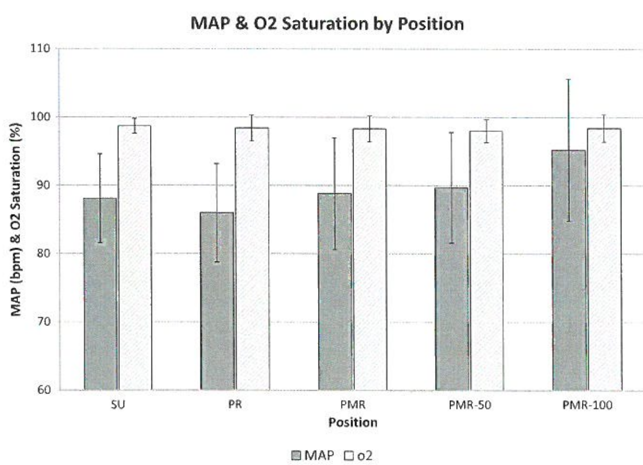

Fig. 5. Mean MAP and oxygen saturation with standard deviation bars.

In our study, we randomized all positions including SU, PR, and PMR with varying weight forces, and calculated CO from direct echocardiographic and sonographic measurements of the left ventricular outflow tract. Consistent with previous investigators we noted a decrease in the diameter of the IVC with the weight force. However we found no differences in CO between any of the positions with and without weight force. In addition, similar to other studies, we found no or minimal changes in vital signs including HR and BP in all the prone positions. Without change in CO and no evidence of hemodynamic compromise on vital signs, these observations do not support the hypothesis that sudden cardiovascular collapse occurs as a result of decreased venous return secondary to chest compression. Our data suggests that although there may be a minimal decrease in SV there is a compensatory increase in HR such that CO does not fall. Additionally the lack of change in O_2 sat further supports our observation that no clinically important change in CO occurred.

Consistent with prior studies, in our study IVC decreased with the heaviest weight force. Despite this decrease there were no syncopal or pre-syncopal events, no episodes of SBP dropping below 100 mmHg, no change in CO, and no complete IVC collapse on ultrasonography in any of the randomized groups.

In summary, our findings do not support the contention that PMR with or without weight force up to 100 pounds results in a decrement in CO sufficient to cause an inherent risk of cardiovascular collapse. These findings are consistent with field case reports in which similar sudden deaths occurred in non-prone and non-PMR positions. These findings are also consistent with a recent large prospective epidemiologic study of police use of force in which prone position was not found to be associated with sudden death.[28] As such it appears another cause of cardiovascular collapse is more likely in these cases than decreased CO secondary to prone position with weight force.

5. Limitations

This study was conducted in male human volunteer subjects who were recruited from a university campus, who were generally healthy and in a controlled environment. We did not replicate all potential conditions in the field including physical exertion, psychological stress, drug intoxication, and trauma, which might impact cardiovascular function and hemodynamic status. However it is difficult to postulate a mechanism whereby these factors would affect our results as most of these factors would in all likelihood increase cardiac output.

We also limited our applied weight force to 50 and 100 lbs. It is possible larger amounts of force are used in actual practice in the field when restraining combative individuals but based upon our review of the literature, we believe these weights would be adequate to detect any significant impact on cardiovascular function were they to occur.

6. Conclusions

Cardiac output is not significantly affected by the PMR as compared with the prone or supine positions, with or without application of 50 or 100 pounds of weight force to the back.

Ethical approval

Not required.

Funding
None.

Conflict of interest
None declared.

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